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Substorm Theories: Are They Converging?

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1. Introduction

It is my intention to provide a critique of proposed substorm onset mechanisms in light of theoretical, and current, broad, observational constraints as perceived by this researcher. Various connections or unifying aspects among the various theories will be suggested or implied in the course of this presentation. A critical report on the then-current state of substorm research was given by *Fairfield* [1992]. Many of the physical issues concerning substorm onset mechanisms were nicely discussed. I will assume the reader is familiar with that article rather than repeat what is contained there. Some overlap is unavoidable, but I will attempt to provide additional, different perspectives.

1.1. Substorm Onset Mechanisms

In Table 1 of *Fairfield* [1992] proposed substorm onset mechanisms are summarized. I mention a few more. The basic mechanisms proposed as responsible for substorm onset can be classified as reconnection, current disruption, M-I coupling, ballooning, and boundary-layer processes. The classifications are fuzzy. However onset may be initiated, reconnection probably plays a role in substorm expansion, current disruption accompanies dipolarization, and M-I coupling occurs in all phases of convection. The classifications refer to the major active process responsible for substorm onset. As we will see, the compartmentalization of proposed mechanisms tends to disappear as the roles of these mechanisms in M-I coupled convection and the substorm process are analyzed.

Reconnection theories include those of *Atkinson* [1967] in which impulsive reconnection in the tail and the resulting earthward flow of flux tubes was used to explain the geomagnetic bays and auroral bulge observed during substorms. *Schindler* [1974] and coworkers suggest that onset occurs when the tearing mode goes unstable. *Baker and McPherron* [1990] suggest that slow reconnection occurs in the closed plasma sheet during the growth phase and onset occurs when reconnection reaches the lobes.

The current disruption theories are classified as those of *Lui et al.* [1990, 1991, 1993], *Mitchell et al.* [1990], and *Tsyganenko* [1989]. In the Lui et al. and Mitchell et al. models it is proposed that as the plasma sheet thins to the order of an ion gyroradius, the ions demagnetize and can stream duskward at a significant fraction of their thermal velocity and/or provide a significant fraction of the cross-tail current. Lui et al. suggest that a kinetic cross-field streaming instability disrupts this current; Mitchell et al. suggest that the energetic ions run out. Tsyganenko suggests that current disruption accompanying the isotropization of anisotropic pressure in the current sheet results in dipolarization.

The M-I coupling theories are classified as those in which the substorm is triggerred by a process centered in the ionosphere. I will use the phrase "M-I coupled convection" to refer to processes in which the ionosphere plays a cooperating role with magnetospheric processes. M-I coupling models must further be distinguished from auroral breakup models [e.g., *Heppner et al.*, 1967; *Coroniti and Kennel*, 1972; *Rothwell et al.*, 1991]. In

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the former, magnetospheric unloading, i.e., dipolarization is triggered. In the latter, breakup is powered by fast convection which may have been triggered by some other mechanism. The prominent M-I coupling model is that of *Kan et al.* [1988] and *Zhu and Kan* [1990] which models growth-phase intensification of the electrojets. *Kan* [1993] suggests that current disruption and dipolarization, i.e., unloading, can be triggerred as an Alfven wavefront launched from the ionosphere arrives in the equatorial plasma sheet. Similarly, the rarefaction wave model of *Chao et al.* [1977] consider the feedback of the polarization electric fields in the Coroniti-Kennel model on plasma flows near the inner edge of the plasma sheet which causes the inner part of the plasma sheet to lurch earthward, launching a rarefaction down the tail. In *Haerendel's* [1992] auroral-avalanche model, as energized plasma piles up in the inner plasma sheet during convection, this plasma undergoes fast lateral escape as auroral arc formation looses frictional control of the plasma. This launches an outward propagating expansion wave which results in fast earthward flows and dipolarization. The *Lundin et al.* [1991] model invokes a low-latitude boundary layer dynamo to explain the progression of auroral intensifications and substom onset reported by *Elphinstone et al.* [1991] using Viking imager data as a solar-wind pressure enhancement passed Earth. Auroral intensifications result when the cross-tail and existing field-aligned currents increase owing to the LLBL dynamo. The exact mechanism leading to current disruption and the substorm current wedge is not considered. According to Lundin et al. the effect will be a dramatic increase of the conductance along the nightside ionospheric path. The LLBL dynamo current will then have a high-conductance path through the ionosphere, resulting in tail current sheet disruption. Since the key suggestion in this scenario is shunting of cross-tail current through a high-conductivity strip in the ionosphere, I will categorize this as an M-I coupling model.

Ballooning is analogous to a Rayleigh-Taylor instability where the roles of density and the gravitational force are replaced with pressure and its force. It is akin to the interchange instability with a larger parallel wave number. Ballooning theories for substorm onset have been suggested by *Roux et al.* [1991] and *Erickson and Heinemann* [1992]. In the Roux et al. model an unstable surface wave grows along the boundary between dipolar and tail-like flux tubes in the inner-edge region of the plasma sheet. In the case examined the wave propagated westward and a westward travelling surge was associated with each period of the wave. Erickson and Heinemann suggest that substorm onset occurs when inward/outward normal-mode oscillations of the plasma sheet, usually stabililized by compression, go unstable. Compressional stabilization is nullified by upward flowing ions associated with upward field-aligned current and corresponding parallel electric field, resulting in the outward displacement of the equatorial plasma pressure profile. This puts the near-Earth plasma sheet out of pressure balance with the lobes. Collapse results and launches a rarefaction down the tail. I will return in §3 to discuss current disruption, tearing, ballooning, and M-I coupling as onset mechanisms.

The boundary-layer theories include the Kelvin-Helmholz instability along the low-latitude boundary layer [*Rostoker and Eastman*, 1987] and the thermal catastrophe model [*Goertz and Smith*, 1989]. In light of the Kiruna conjecture (§2.1), not too much attention is given to these models in this presentation.

2. Observational Constraints

There are several, broad, observational considerations which this researcher perceives as particularly constraining on substorm theories. While some of the observations are better established than others, each can provide useful insight into the substorm mechanism or a test on a substorm concept. In §3 these observational constraints will be used in this fashion.

2.1. The Kiruna Conjecture

It is now the community consensus, known as the "Kiruna Conjecture", that "the auroral substorm onset is very closely coupled to events in the geosynchronous region" [*Kennel*, 1992]. It was clear in the late '60s that it was the equatorwardmost arc which brightened first, and breakup evolved poleward. The location of the initial breakup arc was known to be near the poleward boundary of diffuse aurora or the trapping boundary, which we identify as the inner-edge region of the plasma sheet, in the midnight sector. On page 223 of his book *Akasofu* [1968] states, "therefore, the first indication of the magnetospheric substorm should be the sudden activation of the process that is responsible for the generation of auroral particles near the trapping boundary in the midnight sector."

A review of the history of the substorm debate of the '70s and '80s would be too lengthy to include here. Using Ogo-5 data, *McPherron et al.* [1973] presented an observationally-based description of the substorm which emphasized the substorm current wedge resulting from local current disruption initiated near Earth in a thin current sheet. *Hones et al.* [1973] emphasized near-Earth X-line formation at onset in their observationally-based description inferred from Vela and Imp data. Their observations were summarized by the Hones' cartoon [*Hones*, 1977]. *Lui et al.* [1977] used Imp-6 observations to argue against near-Earth reconnection and offered the rarefaction wave model [*Chao et al.*, 1977]. *Hones and Schindler* [1979] countered with an analysis of Imp-6 and Imp-8 data supportive of near-Earth reconnection and against the rarefaction model. MHD simulation codes showed substorm-like reconnection [e.g., *Birn*, 1980], while ISEE-3 observations of substorm-associated plasmoids in the far tail [*Hones et al.*, 1984] were supportive of the near-Earth X-line model.

At the same time there was some confusion in the community about the mapping of the central plasma sheet (CPS) and boundary plasma sheet (BPS) of *Winningham et al.* [1975] and the central plasma sheet (CPS) and plasma-sheet boundary layer [*Eastman et al.*, 1984]. Since the PSBL is associated with an X-line and the discrete precipitation in Winningham et al.'s BPS is associated with arcs and substorms, an understandable confusion arose within the open-model paradigm. The near-Earth X-line model of substorms, summarized by the Hones' cartoon, was the beneficiary.

Since AMPTE the situation seems to have been clarified. *Baumjohann et al.* [1990] showed that within AMPTE/IRM apogee (~ $19R_E$), fast flows are predominantly earthward; tailward flows are infrequent. If an X-line forms in association with substorms, it appears that it forms tailward of $19R_E$. Multi-satellite observations involving AMPTE and geosynchronous satellites [e.g., *Lopez and Lui*, 1990] show the close association in time between first signs of onset in the near-Earth plasma sheet and ground onset. At the same time, the confusion between Winningham et al.'s CPS-BPS transition and the PSBL was clearing. The review by *Galperin and Feldstein* [1991] clarified the relationship between auroral morphology and magnetospheric plasma domains, including the return of the breakup arc to low *L*-shells (within $10R_E$). It was my impression at the Kiruna meeting that the community now accepts both the Galperin-Feldstein renaissance and that substorm onset occurs locally near-Earth in the absence of reconnection signatures, and its effects expand radially and in local time. *Kennel* [1992] offers the "strong version" of the conjecture, "...plasma sheet reconnection and plasmoid formation do not always have to occur in close temporal and spatial proximity to the events defining the geosynchronous substorm."

After Kiruna, advocacy for the boundary-layer theories diminished. However, as described by *Lui* [1991], instabilities along the boundary layers probably account for many of the features of the aurorae later in the expansion. Near-Earth onset as well as other observational inconsistencies [e.g., *Baumjohann et al.*, 1991] and theoretical questions are problematic for the thermal catastrophe theory as the substorm onset mechanism. However, the close temporal relationship between events at geosynchronous and ground onset does not rule out the tearing mode or some other global instability as the cause of substorm onset. If onset is the result of a large-scale instability such as the tearing mode, then the near-geosynchronous region and the plasma sheet near 20-30R_E can go unstable together. Signatures of onset need to be examined in the context of large-scale physical processes such as MHD instability.

2.2. *The Substorm Current Wedge/Unloading*

It is clear that substorms involve the loading and unloading of plasma and magnetic flux in the geomagnetic tail. The substorm current wedge is closely associated with the unloading process. The exponential time behavior of the electrojets (*AE*) [e.g., *Weimer,* 1992] commencing at substorm onset and the associated energy release make it clear that the substorm involves unloading of previously stored plasma and magnetic flux in the tail. Development of the substorm current wedge is observed to begin in the near-Earth plasma sheet between geosynchronous distance and ~11R_E in a narrow local-time sector and to expand both radially and in local time. The observations of, for example, *McPherron et al.* [1973], *Nagai* [1982], and *Lopez and Lui* [1990] are all consistent in this regard. Understanding the cause of the substorm current wedge and its expansion is synonymous with understanding the cause of substorm onset.

There is abundant evidence that plasmoids (or travelling compression regions, TCRs) are closely associated with substorms *[Moldwin and Hughes,* 1993; *Slavin et al.*, 1984]. The complexity of the structures and the uncertainty of the observations, however, make this observational "fact" less certain than the other features mentioned above. Theoretically, the observations are intelligible if an enhanced rate of return magnetic flux to the dayside during the expansion phase is to involve more than just the flux located within about 20-25R_E of Earth. Without reconnection and the release of energetic plasma from previously closed flux tubes, according to the pressure-balance inconsistency argument [*Erickson and Wolf,* 1980] rapid return transport of the magnetic flux will be blocked. Reconnection can occur along an X-line, or in a patchy fashion as an enhanced rate of formation of Pontius-Wolf bubbles or bursty bulk flows [*Pontius and Wolf,* 1990; *Angelopoulos et al.*, 1992; *Chen and Wolf,* 1993; *Kennel and Angelopoulos Report*] within a "neutral sheet", perhaps with coalescence of newly-disconnected flux tubes into the more familiar plasmoid which at some point can escape downtail.

2.3. *Steady Magnetospheric Convection Events*

Steady magnetospheric convection (SMC) events, as reported by, for example, *Pytte et al.* [1978] (referred to then as convection-driven negative bays) and *Sergeev and Lennartsson* [1988], are relatively long periods (several substorm time scales) characterized by a steady solar wind carrying a southward IMF, enhanced convection evidenced by enhanced electrojets, and the absence of usual substorm signatures. Typically, an SMC starts after a substorm and ends with an IMF change triggering a substorm. During the SMC, activity appears to be directly driven by the solar wind. Recently, *Sergeev et al.* [1993b] reported on near-Earth plasma-sheet observations, supplemented with ground-based and low-altitude observations [*Yahnin et al.*, 1993], which may carry important implications for the role of tearing, current disruption and chaos in the plasma sheet. Combine their observations with previous midtail observations [*Sergeev and Lennartsson,* 1988], Sergeev et al. infer a magnetospheric configuration consistent with the steady-state adiabatic convection solutions of *Hau et al.* [1989] and *Hau* [1991]. The observations during SMCs reveal an often extraordinarily deep magnetic field depression and intense current density in the near-Earth plasma sheet. Sergeev et al. ask the question, "How can such a stressed configuration with such a thin and intense current sheet in the near-Earth tail remain stable during many hours?"

Note that thin current sheets, with thicknesses comparable to typical ion gyroradii, are commonly observed near Earth prior to substorm onset or local current disruptions. (See *Pulkkinen et al.* [1992], *Sergeev et al.* [1993a] and references therein; also *Pulkkinen* [this report].) As in the SMC event, such thin, intense current sheets can exist for tens of minutes prior to onset.

If these observations are correct, then it seems that substorm onset mechanisms that depend only on the strength of the cross-tail current, the thickness of the current sheet, the equatorial magnetic field strength or its gradient, or the strength of ionospheric electrojets are not, in themselves, responsible for substorm onset. Tearing mode, current disruption or M-I coupling theories would be incomplete with respect to being the substorm onset mechanism. It would seem that something else is needed to trigger these mechanisms before they can play an important role in substorm expansion. An important caveat to this supposition is the role of B_y in the tearing mode or current disruption. (See the discussion by *Sergeev et al.* [1993a].)

2.4. *Pseudobreakups*

To borrow the definition referred to by *Koskinen et al.* [1993], pseudobreakup is a term used "to describe auroral activation phenomena that look like auroral breakups but do not evolve into a full-scale expansion phase." Their similarities to substorm onsets include a burst of Pi2 micropulsations and a weak enhancement of the westward electrojet. The determination of the difference in magnetospheric and ionospheric conditions between pseudobreakups and substorm onsets should provide valuable clues for understanding these phenomena. *Akasofu* [1964] suggests that a pseudobreakup results when an activation occurs on other than the most equatorward arc. *McPherron et al.* [1973] stress the localization of current disruptions to a limited local-time sector of the plasma sheet originating near the inner-edge region of the plasma sheet. Using Viking imager data, *Shepherd and Murphree* [1991] note a multiplicity and spatial separation in both longitude and latitude of local auroral arc intensifications in the ten or so minutes preceeding substorm onset. They also note that the most striking feature of substorm intensification is the "simultaneity" (within one-minute resolution) of the intensification along a broad longitudinal extent, contrary to observations of the local development and subsequent latitudinal and longitudinal expansion of the substorm current wedge noted in §2.2. Recently, *Elphinstone et al.* [1993] noted an azimuthal periodicity (spacing 200 to 400 km) in auroral luminosity in the few minutes before onset in 27 of 37 events studied with Viking imagery.

Both *Koskinen et al.* [1993] and *Ohtani et al.* [1993] report on near-Earth plasma sheet observations of current disruptions associated with pseudobreakups. An intriguing feature of these observations is that after local dipolarization associated with the pseudobreakup, 20 minutes passed before the next local dipolarization was observed at the satellite. During this interval local observations indicate that the plasma sheet resumed its growth-phase characteristics. In the Koskinen et al. event, the magnetic H component reduced to its pre-dipolarized value during this period, at which time dipolarization associated with a substorm onset was observed. In the Ohtani et al. event, the H component did not reduce to its pre-dipolarized value during the 20 minutes before a weaker pseudobreakup disruption was observed. It should be noted that the Ohtani et al. events occurred when the solar wind was fairly quiet and the IMF-B_z component was near zero as it slowly shifted over a few hours from northward to southward. Koskinen et al. noted that while the magnetospheric disturbance was limited in local time, weak disturbances in the ionosphere covered several hours. Ohtani et al. assumed that the electrojet's width in the ionosphere mapped to the latitudinal extent of the current disruption. The difference in signatures observed at two satellites, spaced closely in longitude, was due to a limited radial extent of the disruption.

Unfortunately, plasma flow information is not available with these reports of current disruptions. I suggest that additional observations and analysis are warranted to distinguish localized, isolated, current disruptions, interpreted as pseudobreakups, from the passage of a bursty bulk flow over the satellite, which originated farther down tail. The locally observed magnetic and particle signatures of local current disruptions have many similarities to signatures associated with passage of a bursty bulk flow, e.g., the "local auroral flares" described by *Sergeev et al.* [1986]. Of course, it could be that a local current disruption is the origin of a bursty bulk flow with associated region-1 sense current wedge and local geosynchronous injection.

2.5. *The Explosive Growth Phase*

Ohtani et al. [1992] used AMPTE/CCE to report on the initial signatures of nearby current disruption. They identify two types of signatures depending on whether the spacecraft was located earthward or tailward of the nearby disruption. A significant result of their study is the identification of the explosive growth phase. The explosive growth phase is the rapid (~1 minute), several-nT depression of the magnetospheric H component just prior to local dipolarization. Ohtani et al. interpret this as resulting from an explosive enhancement in tail current intensity tailward of the satellite in the short period prior to current disruption.

2.6. *Pre-Onset Fading of Arcs*

Often pre-breakup arcs are observed to fade during the minute or two prior to breakup [e.g., *Pellinen and Heikkila,* 1978; *Pytte et al.*, 1976; *Shepherd and Murphree,* 1991]. There is a simple explanation for this phenomenon (see §3.1) which helps shed some light on the onset mechanism and possibly on the distinction between pseudobreakups and substorm onset.

3. Theoretical Considerations

In this section I consider the various classes of proposed onset mechanisms -- M-I coupling, ballooning, current disruption, and reconnection -- in more detail. I suggest that when viewed within the framework of the large-scale stability of the magnetotail, the various proposed mechanisms appear to operate simultaneously to result in either a pseudobreakup or substorm onset. As each of the proposed mechanisms is examined in this context, its distinction from the other proposed mechanisms tends to blur. This also makes difficult the ordering of the following subsections; I ask the reader to tolerate the cross-referencing between the various proposed onset mechanisms.

3.1. *M-I Coupling*

To understand the substorm onset mechanism we must ask, "What can cause the diversion of cross-tail current through the ionosphere in the substorm current wedge?" Is the current disruption associated with substorm onset triggered by the eastward polarization current in an Alfven wavefront launched from the ionosphere as suggested by *Kan* [1993], or because it is easier for the cross-tail current to shunt through a high-conductance strip in the ionosphere rather than flow across the plasma sheet as suggested by *Lundin et al.* [1991]?

To investigate this question suppose that the ionospheric current increases in a channel, beyond that supplied by field-aligned current generated in the magnetosphere. This might happen as the equatorial curvature of field lines increases during the growth phase, and, for example, *L*-shell splitting occurs at the boundary of trapped energetic electrons (>*30* keV). These electrons isotropize and some scatter into the loss cone (see e.g., *West* [1979] and *Pulkkinen et al.* [1992]). These energetic electrons can reach E-region altitudes, and each can produce many ion-electron pairs (one pair per 35 eV of incident energy). The ionospheric current can increase, for a given imposed westward electric field, faster than field-aligned current is being provided by the magnetosphere. The ionosphere becomes polarized as positive (negative) space charge accumulates at the westward (eastward) end of the conductive strip. To equilibrate the charge along field lines, an Alfven wavefront is launched to transmit the eastward polarization electric field into the magnetosphere. Behind the eastward (westward) side of the wavefront is upward (downward) field-aligned current. The $\mathbf{E} \times \mathbf{B}$ velocities of field lines slow as the Alfven wavefront propagates. Along the wavefront is an eastward polarization (inertial) current. The equatorward ends of the field lines convect at the unperturbed $\mathbf{E} \times \mathbf{B}$ velocity until the wavefront arrives there. During the transit time of the wavefront from ionosphere to equatorial magnetosphere, the field lines become more dipolar reducing their curvature, and the $\mathbf{E} \times \mathbf{B}$ speed slows. This reduces or turns-off the source of the energetic electrons which started the process.

The eastward inertial current, $\sim\mathbf{B} \times dv/dt$, is associated with the braking of the flow, and a transient field-aligned current is associated with the (oblique) Alfven wave. As the convection slows, the magnetospheric generator of field-aligned current is reduced [*Vasyliunas*, 1972; *Erickson et al.*, 1991]. An Alfven wave will be sent to the ionosphere to carry the reduced field-aligned current. Even before the message is received, recombination reduces the ionospheric conductivity, since the energetic electrons were super-Alfvenic [see *Kan and Tamao*, 1988]. (Note that the model of *Zhu and Kan* [1990] includes precipitive enhancement of the ionospheric conductivity and the recombination-time effect; recombination times are 15-30 seconds while the Alfven transit times are a few minutes.)

This discussion is similar to the explanation for auroral fading given by *Pellinen and Heikkila* [1978]. As ionizing precipitation causes an electrojet to intensify, ionospheric feedback results in the braking of convection and the reduction of the ionization source. (Pellinen and Heikkila note that during auroral fading fluxes of precipitating ions and electrons behave similarly.) If the magnetospheric driver is not too intense, then the ionospheric polarization field will be successfully communicated to the magnetosphere, field-line curvature decreases, convection slows down, and the arc fades. (Is this a pseudobreakup?) If the magnetospheric driver is just too strong, say owing to a magnetospheric instability with a growth time comparable to the Alfven transit time, then the ionosphere is helpless to prevent breakup. The arc might fade for a minute or two, but will reintensify with a vengeance. *Kan* [1993] suggests that during the expansion phase, electrojet polarization and the resultant Alfven wavefront can provide a positive feedback in the dipolarization process. Note that the ionospheric feedback is such as to reduce the westward electric field and slow convection. The key event of the substorm is the rapid return rate of magnetic flux transport to the dayside. The ionosphere tends to resist rapid changes in the magnetosphere.

I will refer to the above discussion as the "fading" scenario in M-I coupled convection. The effects of polarization currents and fields become more difficult to diagnose as one considers the braking of flows in the inner-edge region of the midnight plasma sheet owing to the "shielding" effect. This discussion will encompass the remainder of the M-I coupling models for substorm onset mentioned in the introduction. As discussed and modeled by *Harel et al.* [1981], a combination of gradient/curvature drift (pressure gradients) and corotation conspire to produce the region-2 field-aligned current system. The region-2 currents rotate the convection electric field in the plasma sheet from duskward to radially outward (inward) along the duskside (dawnside) inner-edge region of the plasma sheet. This shields the inner magnetosphere from plasma-sheet flows, turning flows azimuthally to convect toward the dayside. This discussion is again eased if we speak in terms of space charge, which is more directly related to electric fields. Associated with duskside (dawnside), downward (upward), region-2 currents is positive (negative) space charge. In addition to the region-2 currents are the upward field-aligned currents associated with the Harang discontinuity [see *Erickson et al.*, 1991]. The low-latitude extent of these currents (negative space charge) extends from dawnside region 2 duskward, to overlap duskside region 2 and intensify the tailward electric field just westward of the stagnation point of the earthward plasma-sheet flow.

Associated with the braking of the earthward convection will be an eastward inertial current as in *Haerendel's* [1992] auroral-avalanche model. As well, radially outward (duskside) and inward (dawnside) inertial currents will be associated with the azimuthal acceleration of the convection. Throughout most of the growth phase these inertial currents are small. The shielding (including the Harang system) described above is modified only slightly by these inertial effects. If convection drives upward field-aligned current at a rate faster than electrons scatter into the loss cone, then field-aligned potential drops will develop to open the electron loss cone. However, this only strengthens the shielding electric field.

On the other hand, it might be that the transition from dipolar to tail-like flux tubes, which develops in association with the intense near-Earth current sheet late in the growth phase, narrows the shielding layer such that the turn of the convective flow from earthward to westward occurs within a radial extent comparable to typical ion gyroradii. In this event, inertial effects will be significant and a positive feedback might result in which negative space charge builds up in association with the westward turning. This would resemble Haerendel's auroral-avalanche model or that of *Chao et al.* [1977] in which fast removal of flux tubes at the shielding layer launches a rarefaction down the tail.

Careful modeling of this complex scenario should be performed to determine its feasibility. Modeling should include the possible polarization of the ionospheric electrojet as discussed in the "fading" scenario; positive polarization charge at the westward end of the electrojet will tend to neutralize the negative, magnetospherically-generated space charge and resist acceleration of the flows. A further complication in the M-I coupled convection picture comes about because of the redistribution of plasma pressure along field lines when parallel potential drops exist. This could have interesting consequences in connection to the ballooning instability considered in §3.3.

It appears that substorm onset is triggered in the magnetosphere, not in the ionosphere. As discussed by *Opgenoorth* [1992] at last year's workshop, the ionosphere may provide more feedback to the magnetosphere during prolonged active periods or during multiple substorm onsets as the neutral winds and the Hall conductance are enhanced.

This discussion does not deny that M-I coupling plays a role in substorm onset; it may play a critical role. The role of M-I coupling, as well as the role of the other proposed mechanisms for substorm onset, must be examined in the context of the stability of the magnetospheric configuration.

3.2. MHD Stability

Given the unloading nature of onset and expansion and the energy involved, it is reasonable that the large-scale stability of the plasma sheet is involved in the substorm process. *Erickson and Heinemann* [1992] have applied MHD energy-principle analysis to two-dimensional, magnetospheric, self-consistent, adiabatic convection sequences [*Erickson*, 1992]. The analysis reveals that frozen-in normal modes are stable when no mass is exchanged between plasma-sheet flux tubes and the ionosphere. This is consistent with the results of *Birn and Hones* [1981] using three-dimensional, time-dependent, MHD simulations, *Lee and Wolf* [1992] who assumed large k_y, *Ohtani and Tamao* [1993] who considered the coupling of Alfven and magnetosonic waves in inhomogeneous plasma, and others, which shows that the magnetosphere is stable against ideal-MHD ballooning. Indeed, the results show that the magnetosphere becomes more stable as the tail stretches during the growth phase.

The situation changes when mass enters or leaves flux tubes. *Schindler* [1974] suggested that the ion tearing mode is the mechanism by which plasma is released from stretched plasma-sheet flux tubes and the tail relaxes to a less-stressed state with the explosive release of energy sufficient to account for that dissipated in substorms. Another way mass can enter or leave flux tubes is to exchange mass with the ionosphere. Erickson and Heinemann tested the stability of magnetospheric equilibrium against isobaric fluctuations. As flux tubes expand or contract, constant pressure is maintained by mass exchange with the ionosphere. (I return to the questions this raises below.) The energy principle in this case is the same as used by Schindler and coworkers, except that they applied the analysis to asymptotic tail equilibria, whereas Erickson and Heinemann applied the analysis to magnetospheric equilibria, which included a plasma-sheet inner-edge region. Our results were consistent with those of Schindler and coworkers; a non-flared plasma sheet is stable whereas a flared plasma sheet is unstable. In addition, even in a non-flared plasma sheet, stability is lost when a local minimum in equatorial field strength, B_e, develops in the self-consistent convection sequences. Likewise, the steady-state convection solutions of *Hau et al.* [1989] are unstable.

The general result is that the plasma sheet is stable to compressional, frozen-in fluctuations. However, the plasma sheet is unstable to the growth of isobaric modes when the plasma sheet flares or possesses a local minimum in equatorial field strength. The stable fundamental mode is just the inward/outward oscillation of plasma-sheet flux tubes and has a period of a few minutes (frequency of a few mHz). Mechanical work, *pdV*, exerted as flux tubes expand or contract provides the restoring force. If the *pdV* work can be nullified, so that the expansion or contraction occurs at constant pressure, ballooning can occur. (Actually, isobaric behavior is not required on a local flux tube, rather that an expanded (contracted) flux tube have a local pressure greater (less) than the pressure at that location in the unperturbed equilibrium.) The unstable modes can have growth times as short as a few minutes. Generally, the deeper the minimum in B_e or the more the plasma sheet flares, the shorter the growth times. Introduction of a finite k_y, as occurs in the model of *Roux et al.* [1991], had little effect on the results, and the configurations were stable to interchange. Hau's steady-state solutions are metastable to interchange outside the inner-edge region, stable within.

The ideal mode in which near-Earth flux tubes expand tailward, which requires that ions flow upward from the ionosphere, corresponds to the "protoplasmoid" or "global ballooning" description of Erickson and Heinemann. The ideal mode in which near-Earth flux tubes contract earthward which requires that ions flow down into the ionosphere, corresponds to the "ideal tearing mode" description of *Birn et al.* [1993]. Ideal paths to instability are discussed next. Following that, the non-ideal paths to instability (current disruption and tearing) are discussed. In both discussions, a critical role for M-I coupling of convection is revealed.

3.3. Ballooning

The ideal ballooning modes can come about owing to M-I coupling of convection. As discussed in §3.1, a portion of the upward Harang field-aligned current system will exist just poleward (tailward) of the duskside region-2 currents (i.e., the equatorward side of the Harang electric field reversal). This upward current could be particularly intense in association with the braking of earthward plasma-sheet flow and its westward acceleration in the inner-edge region near midnight. Associated with the upward currents (owing to diversion of gradient/curvature drift current alone) can be upward potential drops and upward flows of ionospheric ions. *Erickson and Heinemann* [1992] show that observed potential drops and upward ion fluxes are adequate to allow near-Earth flux tubes to expand tailward at constant pressure. A $1R_E$ tailward displacement at constant pressure requires about a 2% increase in the energy content of a near-Earth plasma-sheet flux tube. This energy is comparable to the loss of flow energy during braking of 30 km/s earthward flow. So, it appears that ballooning is feasible. This increase in energy content does not have to be provided entirely by acceleration of ionospheric ions into flux tubes. As the upward currents increase late in the growth phase, they might exceed the rate in which electrons are scattered into the loss cone. A parallel electric field will be required to open the equatorial loss cone. Assuming a Maxwellian, the ion distribution and its pressure will shift toward the equator,

$$P_i \sim exp[-(mv^2/2 - e\phi)/kT_i].$$

For an ionosphere-to-equator potential drop comparable to the electron thermal energy per charge, and $T_i/T_e \approx 7$, an approximate 16% equatorial shift in the pressure distribution along the field line will occur. For the stretched flux tubes late in the growth phase, the equatorial displacement is substantially a tailward displacement. (The pressure gradient scalelength in the near-Earth plasma sheet should be several R_E at this time.) While this occurs, the lobe magnetic pressure is essentially unperturbed. Since the pressure gradient is earthward, tailward displacement of the equatorial pressure profile results in $P_{lobe} > P_{eq}$ near the inner edge, and $P_{lobe} < P_{eq}$ tailward of the inner edge. If the pressure displacement occurs over too-limited a radial extent, flux tubes on either side will be over- and under-compressed, and the mode will be stabilized. (A pseudobreakup?) If however, pressure displacement occurs over a radial extent comparable to the plasma-sheet thickness, then the vertical pressure imbalance can be communicated to the lobes before the radial compressional mode can provide stabilization. This results in the out-of-equilibrium "protoplasmoid" or "global ballooning" picture of Erickson and Heinemann. Collapse ensues near the inner edge and launches a rarefaction tailward. Dipolarization occurs on the earthward side of the collapse; forced thinning of the plasma sheet occurs as the collapse travels downtail causing "neutral sheet" or X-line formation.

Various observations are supportive of this scenario. *Daglis et al.* [1994] show that the contribution to near-Earth plasma-sheet pressure from ionospheric ions correlates well with *AU* and poorly with *AL* during the growth phase. The near-Earth portion of the upward Harang currents westward and earthward of the Harang electric field reversal should close via the eastward electrojet (*AU*). (Note that M-I coupling was included in the MHD simulations by *Hesse and Birn* [1991], however, the runs did not include mass exchange with the ionosphere which could affect ion distributions along field lines.) The azimuthal periodicity in auroral luminocity prior to onset noted by *Elphinstone et al.* [1993] (§2.4) could be indicative of azimuthal structure of ballooning as discussed by *Roux et al.* [1991]. Ballooning might be analogous to coronal mass ejections (CMEs) and flares. The CME (global ballooning?) is observed to preceed the occurrence of the flare (indicative of reconnection) [e.g., *Kahler*, 1992]. Similarly, ballooning might explain the observations of *Lyons and Huang* [1992] who find plasma-sheet expansion at $\sim 20\ R_E$ commencing as ground onset is recorded. Finally, while the analysis is not yet complete, CRRES electric field data often shows an oscillation of the westward electric field in the near-Earth plasma sheet in the minutes prior to dipolarization. In many examples an eastward excursion of the electric field occurs just prior to large, westward electric field associated with dipolarization [*Maynard*, private communication].

Little distinguishes the ballooning scenario from the rarefaction wave model discussed in §3.1. In that discussion, as the shielding-layer thickness approached typical ion gyroradii, fast convection of plasma out of the region caused an underpressure near the inner edge. At the same time, decrease of the lobe flux is blocked by the slow convection downtail. *Heinemann et al.* [1993] show that associated with the negative polarization charge which results as the shielding-layer thickness approaches ion gyroradii, an ionosphere-to-equator parallel potential drop of the order of an electron thermal energy per charge must develop. So, the M-I coupling rarefaction model and "global ballooning" seem to describe the same possible scenario for substorm onset, if the rarefaction wave models are augmented with consequent "neutral sheet" or X-line formation during substorm expansion. Note that the ballooning modes should perhaps be described as semi-ideal; the particle drifts, which contribute to those cross-tail currents having a divergence, violate frozen-in-flux but conserve the number of particles on a flux tube [*Wolf*, 1983].

3.4. Tearing/Reconnection

Since *Schindler* [1974] suggested the growth of the ion tearing mode as the mechanism of substorm onset, various researchers have considered the stability of the magnetotail configuration with respect to tearing. The debate over tearing growth rates is still unresolved (see *Fairfield's* [1992] review and *Wang and Bhattacharjee* [1993]). As pointed out by Fairfield, the instability of the ion tearing mode rests on the question of whether magnetized electrons stabilize the mode or whether electrons can be scattered and allow the instability to proceed. For example, *Pellat et al.* [1991] argue that conservation of canonical p_y momentum guarantees that flux-tube content is preserved regardless of whether the motion is adiabatic or not (see also *Wolf and Pontius* [1993]), providing stabilization of the tearing mode in the quasi-neutral plasma by electron compressibility. *Wang and Bhattacharjee* [1993] use a fluid treatment with a generalized Ohm's law relating the perturbation current and electric field and concur with the finding of Pellat et al. However, when they include a magnetic shear component (B_y), they find that electron bounce times can exceed the ion tearing growth time, and electron compressibility no longer provides stabilization. *Esarey and Molvig* [1987] find that electrostatic turbulence resulting in diffusion across the magnetic field can destabilize the tearing mode. Pellat et al. reconsidered this mechanism and found that while the electron tearing mode can exist, the ion tearing mode requires that diffusion exceed the Bohm diffusion rate. *Kuznetsova and Zelenyi* [1991] claim that Pellat et al. did not include the irreversible changes in the perturbed distribution function in their analysis of the effect of pitch-angle diffusion on tearing growth rates. While pitch-angle diffusion conserves the number of particles in a flux tube, Kuznetsova and Zelenyi suggest that the ion tearing-mode growth rate is a good estimate of the rate of spontaneous reconnection.

I admit that I quickly get lost as I try to follow the mathematical debate over tearing-mode growth rates. Let me just mention that tearing analyses assume perturbations on an equilibrium; an equilibrium need not exist as would be the case if the ballooning mode were unstable. Also, none of the analyses consider the effect of field-aligned currents or ionospheric dissipation. Field-aligned currents provide for quasi-neutrality as electron and ion species separate. For example, turbulence generated by the ions (as in the case of the current disruption to be discussed in the next section) will cause finite-Larmour-radius effects providing for the non-constancy of the ion's canonical p_y momentum, and ions can diffuse. The number of electrons on flux tubes can and will adjust to match that of ions via transport of electrons to and from the ionosphere as field-aligned currents. What this means to tearing-mode calculations I do not know, but I will assume that pressure-bearing ions can diffuse with respect to frozen-in electrons by such a mechanism, allowing for release of magnetic tension. Allow me to assume tearing and reconnection are feasible and continue with a few brief comments concerning reconnection models of substorms.

Results from the Lyon-Fedder MHD code were shown both at this workshop and at the Working Group-5 meeting held at Boston College (October 1993). Runs were performed simulating the events preceeding and during the substorm documented in Viking imagery and reported by *Elphinstone et al.* [1991] and *Lundin et al.* [1991]. Synthetic aurora were produced which generally followed auroral development seen from Viking. The Lyon-Fedder code uses a high-order conservative algorithm; X-line formation may proceed owing to numerical dissipation which results as physical scalelengths approach the grid spacing ($\sim 1R_E$ in the near-Earth tail). As the plasma sheet thins to about the grid spacing, plasma diffuses and an X-line forms. Thus, the Lyon-Fedder code invariably models a substorm during southward IMF conditions. As a thin current sheet much less than $1R_E$ thick is often encountered in the near-Earth plasma sheet, sometimes persisting for tens of minutes or hours (see §2.3), the Lyon-Fedder code appears too robust with respect to substorm onset.

Tearing mode simulations have been performed using a variety of physical parameters by Birn and colleagues. Their MHD code models the magnetotail beyond the inner-edge region of the plasma sheet. Dissipation in the code is provided by an explicit assumption for the resistivity. When no resistivity is assumed ($\eta = 0$), the tail remains stable; when resistivity is assumed ($\eta \neq 0$), magnetic diffusion occurs and the tearing mode evolves. The rate of magnetic diffusion is controlled by $\eta \nabla^2 B$. In the usual starting tail configurations assumed in their simulations, variations of the fields down the tail are gradual and the tearing growth rate is slow. *Hau and Wolf* [1987] found a vast increase in the evolution toward a neutral line when a local minimum in equatorial field strength is assumed (owing to $\nabla^2 B$). Such configurations are expected theoretically from the pressure-balance-inconsistency argument [*Erickson and Wolf*, 1980] and quasi-static modeling results [*Erickson*, 1992; *Birn and Schindler*, [1983], as well as from particle simulations [*Pritchett and Coroniti*, 1990] and observationally inferred by *Sergeev et al.* [1993b]. Likewise, a vast increase in the tearing growth rate can be obtained by assuming a spatially varying resistivity (again owing to an increase of $\nabla^2 B$ as diffusion occurs locally) as demonstrated by *Hesse and Birn* [1992].

The three-dimensional simulations by *Birn and Hesse* [1991] and *Hesse and Birn* [1991] show the development of dipolarization and the substorm current wedge. Fast earthward flows result from reconnection downtail (perhaps $\sim 20R_E$) which reduces the pressure-bearing ion content of flux tubes, allowing them to collapse earthward. In these simulations, dipolarized flux tubes pile-up at the earthward simulation boundary, and the region-1 sense substorm current wedge develops from near Earth outward, owing mainly to velocity shear. The results look very much like the substorm development suggested by *Atkinson* [1967]. While dipolarization and the substorm current wedge appearing first near Earth and later downtail is consistent with observations, this comes about in association with fast earthward flows originating further downtail, which might be questioned observationally. In their runs using localized resistivity, the resistivity was chosen to peak at $15R_E$ corresponding to perhaps $\sim 22R_E$ in the magnetospheric tail. I would be interested to see if the development of dipolarization and the current wedge would be more satisfactory if the resistivity peak were chosen nearer Earth, say to correspond to onset of current disruption to be discussed in the next subsection.

Baker and McPherron [1990] suggest that reconnection occurs during the growth phase, and substorm onset occurs as reconnection reaches the lobes. They made this suggestion, at least in part, to account for the intense current sheet near Earth which develops late in the growth phase. They suggested that, rather than divert through the ionosphere, a portion of the cross-tail current near the reconnection region is diverted earthward. There are several problems with this suggestion. One is that given the various intensities of substorms, i.e., the varying amount of return, earthward transport of magnetic flux, it seems that some substorms could be accommodated by the magnetic flux contained only in the closed plasma sheet. I suspect that onset of lobe reconnection corresponds roughly to the poleward extent of the auroral bulge in the ionosphere. Another problem is the divergence of cross-tail current into the near-Earth region is inconsistent with particle drifts. As discussed in the next subsection and substantiated by the simulations of, e.g., *Birn and Hesse* [1991], flux tubes eminating from the diffusion region have reduced particle contents with respect to flux tubes at earlier and later local times which did not take part in the reconnection process. The result is less cross-tail current in the reduced-population flux tubes and enhanced westward electric field. This is totally inconsistent with the suggestion of Baker and McPherron. *Sergeev et al.* [1993a] and *Schindler and Birn* [1993] discuss more reasonable explanations for the development of the thin, intense current sheet near Earth late in the growth phase.

3.5. *Current Disruption*

It has been suggested that the isotropization of anisotropic pressure in the plasma sheet can result in a current disruption leading to substorm onset [e.g., *Tsyganenko*, 1989]. It is reasonable that $p_{\parallel}$ should exceed $p_{\perp}$ as flux tubes shorten during earthward convection. Observations show the ratio of parallel to perpendicular pressure is usually less than 1.1 [*Stiles et al.*, 1978]. *Nötzel et al.* [1985] interpret this as a manifestation of the near-isotropy firehose limit in the high-β plasma sheet. *Mitchell et al.* [1990] infer from their observations of a dipolarization event, that prior to dipolarization a substantial portion of the current density was carried by anisotropic electrons. As the current sheet thinned late in the growth phase, this current was taken over by non-adiabatic ions while the electrons isotropized. It was only as the non-adiabatic ions ran out that current was disrupted and dipolarization occurred. This is consistent with the modeling results of *Lee et al.* [1992] who showed that in the high-β plasma sheet, the difference between the magnetic configuration when the sheet is near the firehose limit and when the sheet is isotropic is minor. A thin, intense, anisotropic current sheet can exist within a broader isotropic sheet as suggested by, e.g., *Tsyganenko* [1989] and recently reported by *Sergeev et al.* [1993a].

I suspect that the ions just didn't run out in the Mitchell et al. observations as they supposed, rather they re-magnetized. This post-midnight current disruption event occurred some 18 minutes after a substorm onset. I suspect the eastward leg of the current wedge passed the satellite as the magnetic field dropped suddenly during the few minutes before current disruption. After the disruption energetic particle fluxes were enhanced and isotropized. This brings us to the cross-field current instability (CFCI) proposed by *Lui et al.* [1990, 1991, 1993] to be the substorm onset mechanism.

I have little reason to doubt that current disruption as described by Lui et al. often occurs in association with local dipolarization in the near-Earth plasma sheet as seen in the events reported by, e.g., *Lui et al.* [1988, 1992]. As for the other proposed mechanisms, the question to be addressed below is, "What is its possible role in the onset of the magnetospheric substorm?" The CFCI as described by *Lui et al.* [1990, 1991, 1993] is a class of kinetic cross-field streaming instabilities akin to the modified two-stream instability (MTSI). For propagation parallel to $\mathbf{B}$ ($\theta = 0$), *Lui et al.* [1993] have performed quasi-linear analysis of the ion Weibel instability (IWI). Linear analysis was performed by *Lui et al.* [1991] for the MTSI. (I will just refer to the CFCI as the MTSI for $\theta \neq 0$.) The lower-hybrid drift instability is stabilized by high plasma β [e.g., *Huba and Papadopoulos*, 1978]. This mode will not be considered here except to note that, if the plasma sheet thins fast enough, say with substorm-sized electric fields, the central plasma sheet may be unstable to the so-called "driven" lower-hybrid modes [*Papadopoulos et al.,* 1990]. The quasi-linear analysis relates the local growth of wave amplitudes with the local evolution of the ion distribution function. The free energy associated with the streaming component of the ion distribution powers the waves. It is important to note that the mathematical analysis of the IWI and MTSI is performed in the local approximation and does not say anything directly about dipolarization or height-integrated cross-tail current.

Restating the question above, "Does the CFCI result in a reduction of the height-integrated cross-tail current, or does it merely re-expand the plasma sheet as it reduces the ion streaming?" For each argument of Lui et al. concerning the global implications of the local CFCI, the other side of the argument appears equally valid, if one refrains from observational justification. I will avoid a point by point analysis of the arguments here; the considerations quickly become mind-boggling. Rather, I will make the following points. First, I do not see why the reduction of the current intensity resulting from the CFCI should exceed the increase in current density associated with the onset of ion streaming. The contribution to the total current density of ions streaming across the tail at several hundred km/s must substantially exceed their contribution to the diamagnetic drift current prior to demagnetization. Second, while the calculations of Lui et al. show that the current density can be substantially reduced in a matter of a few seconds, so too the increase in current density attendant demagnetization occurs very quickly. Why should either process affect the lobe field apart from that associated with variations in plasma-sheet thickness? There is not enough time in either process for the lobe flux to change, which involves convective transport. As the plasma sheet thins and ions demagnetize, the ions' gyrovelocities, which contribute to the perpendicular temperature and pressure of the plasma, suddenly becomes cross-field bulk velocity. Unless a dynamo is present with field-aligned currents opposite the sense of the substorm current wedge, rapid polarization of the plasma will occur. Furthermore, the directed energy available from cross-field streaming originated from the dawn-to-dusk convection electric field. Thus, a portion of the energy flux causing plasma-sheet thinning goes into non-adiabatic heating of the plasma sheet through the action of the CFCI. In this sense, the CFCI acts to limit the thinning of the current sheet.

At the same time, however, magnetic diffusion will occur as ions demagnetize and scatter (re-magnetize) owing to the CFCI. *Lui et al.* [1993] estimate that the current disruption mechanism can represent an 11 or 12 order-of-magnitude enhancement of resistivity over its classical value. (The resulting anomolous resistivity of about 10^{-6} s is close to the value ($\sim 10^{-5}$ s) used in the MHD simulations of *Hesse and Birn* [1991].) As the CFCI acts to limit thinning of the current sheet, energetic ions are released from flux tubes. With a reduced energetic ion content, less cross-tail current will exist on these flux tubes resulting in region-1 sense field-aligned current to maintain current continuity. Ionospheric closure results in enhanced westward electric field across these depleted flux tubes, and they will be injected earthward. This is precisely the mechanism of a bursty bulk flow described by *Chen and Wolf* [1993]. The energetic plasma left behind inflates the plasma sheet; the energetic content of flux tubes left behind is enhanced, and earthward convection of these flux tubes is retarded. Thus, lobe-flux transport is stymied. Have I not just described a situation which triggers ballooning but through another path, namely, the CFCI? Again, if diffusion occurs over a radial extent of the near-Earth tail comparable to the plasma-sheet thickness, collapse can ensue. Collapse of the plasma sheet results in forced thinning of the plasma sheet, intensifying the effect of the CFCI and causing the thin sheet to extend downtail ("neutral sheet" formation), whereby the tearing mode can operate at a fast rate and force X-line formation downtail. If, on the other hand, the thin sheet is too localized, some magnetic stress can be released locally resulting in local dipolarization and weak injection, but large-scale instability will not be triggerred. The plasma sheet will resume its growth phase. This describes fairly well the local current disruption events associated with pseudobreakups described by *Koskinen et al.* [1993] and *Ohtani et al.* [1993].

Alternatively, through the action of the CFCI to limit thinning of the current sheet, a thin current sheet can persist for some tens of minutes. A slight enhancement of earthward transport near-Earth resulting from magnetic diffusion associated with the CFCI (perhaps "local auroral flare" activity) will slow the growth-phase pile-up of magnetic flux in the tail. I can speculate that in some circumstances this can permit time for a steady-state configuration to evolve, as described theoretically by *Hau et al.* [1989] and observationally by *Sergeev et al.* [1993 b]. These configurations have a deep local minimun in equatorial field strength just tailward of the shielding layer, an associated locally-thin current sheet, and a thicker plasma sheet farther out in the tail. As they are in a steady state, intensification of the Harang current system and growth of parallel potential drops doesn't occur, and ballooning cannot be triggerred. As the thin sheet and the action of the CFCI is too local, the tearing mode cannot grow. In this case, the large-scale stability of the plasma sheet is maintained.

Finally, I wish to focus attention on an interesting consequence of earthward diffusion of magnetic flux as would occur in association with the CFCI and resistive tearing modes. Being frozen-in, electrons will $\mathbf{E} \times \mathbf{B}$ drift earthward with the diffusing magnetic flux while some ions are left behind. This constitutes a tailward Hall current and earthward polarization electric field. This is a generator ($j_H \bullet E_P < 0$) to drive a meridional field-aligned current loop (carried mainly by electrons) with downward current flowing from the ions left behind and upward current equatorward. The generator is powered by the release of magnetic tension associated with the magnetic diffusion. Except for details about ionospheric conductivity gradients, this is precisely the situation described by *Burke et al.* [1994] to account for the meridional structure of field-aligned currents earthward of a far-tail X-line associated with the PSBL. Note, this field-aligned current loop is opposite the Hall loop generated in an imperfect Cowling channel such as contained in the auroral breakup models referenced in §1. This indicates that the ionosphere is not the driver of substorm onset but may act as a limiter of onset, as in the other functions of the ionosphere described earlier.

4. Summary

In this paper I have attempted to provide critical commentary and some different perspectives on the various mechanisms suggested as responsible for the onset of magnetospheric substorms: M-I coupling, ballooning, tearing/reconnection, and current disruption. The examination of the role of M-I coupling of convection leads to the conclusion that the ionosphere tends to resist onset of fast earthward convection as would occur during substorm expansion, much less initiate substorm onset. However, at the same time, a possible critical role for M-I coupling is revealed in connection to ballooning, current disruption, and tearing. Indeed, as each proposed mechanism is examined, each appears to operate in concert with one or more of the other mechanisms in order for a dynamic release of free energy to occur, believed to mark the onset of the magnetospheric substorm. I have suggested that the important element of current disruption (specifically the CFCI) is magnetic diffusion or the release of pressure-bearing ions from flux tubes. This immediately places us into the realm of tearing modes. At the same time, the CFCI probably acts to stabilize thin current sheets. Forced thinning of the sheet resulting from onset of the ballooning instability might be required to destabilize the sheet. Along each path to substorm onset, M-I coupling appears to restrict or permit these processes to proceed. The proper question might not be, "Which proposed mechanism for substorm onset is correct?", rather, "How do the various suggested onset mechanisms operate together to result in the magnetospheric substorm?"

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